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The effect of the electric field of the atmosphere on cosmic rays

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Abstract
A review of the present-day situation in the experimental studies of variations of cosmic rays during thunderstorms is given. It is shown that these experiments can be a useful tool for studying very interesting physical effects in the electrically disturbed atmosphere. The main emphasis is laid on the experimental verification of the runaway breakdown theory and on the role of cosmic rays in the processes of lightning initiation.

1. Introduction

The history of cosmic rays during their lifetime can be considered as a sequence of acceleration processes. They are accelerated in the sources, in the interplanetary space, in the heliosphere, in the magnetosphere and in the atmosphere. The electric field of the atmosphere is the last chance for cosmic rays to be accelerated once again.

However, at first sight, the influence of the electric field of the atmosphere on the cosmic rays should be negligible. The permanent potential difference between the ionosphere and the ground is of the order of 200–500 kV. Since the energy of primary cosmic rays at any reasonable latitude far exceeds 1 GeV due to deflection by the Earth's magnetic field, the effects caused by this electric field in the primary cosmic ray spectrum have an order much less than 10^{-3}.

However, the local electric fields during thunderstorm periods can be significantly stronger. At the same time, secondary cosmic rays produced by GeV particles can be of much lower energies deep in the atmosphere. So, electric fields can cause some measurable effects in the cosmic ray fluxes. Still, during thunderstorms many other parameters of the atmosphere (pressure, temperature) are strongly variable, giving effects that are of the same order so that the effects related to the electric fields should be separated from all others. The first experiment, in which it was really done, was made at the Baksan Neutrino Observatory by Chudakov[1] and his collaborator Sborshikov who proved the short variations in the intensity of cosmic rays to be related to electric field disturbances [1]. The results of this experiment will

[1] The talk was presented at the session devoted to the memory of A E Chudakov.

be discussed later. Before this, we should describe the experiments that were made without any connection with cosmic ray studies. They were initiated by the hypothesis published by Wilson as long ago as 1925 [2, 3]. Wilson suggested that strong electric fields within thunderstorms should exert an accelerating effect upon electrons produced by the decays of the radioactive nuclei carried in the air. He pointed out that some of these particles should gain more energy from the field than they lost in ionization. Encounters of these accelerated particles with atomic electrons could result in the ejection of fast secondary particles. These secondary electrons when emitted with sufficient energy and in a suitable direction are capable of being accelerated themselves. Thus, it was in fact predicted that the beams of accelerated electrons could be emitted by thunderclouds both upwards and downwards.

2. Early experiments

The first attempt for searching accelerated electrons was undertaken in 1930 by Schonland in South Africa [4]. Using an ionization-electroscope a search was made for beams of down-moving electrons below thunderclouds. The opposite effect was found: a reduction (sometimes by 20–30%) in the intensity of the radiation when active thunderclouds were overhead. The next experiment made by Schonland and Viljoen in 1931–32 [5] searched for correlations of the counting rate of a Geiger–Müller tube with distant lightning flashes. It was discovered that in some cases, impulses of the Geiger–Müller counter coincided with lightning flashes. These impulses and others, which occurred a few seconds before discharges, were ascribed by the authors to radiation emitted by thunderclouds. Halliday [7] tried to observe the same type of coincidences by synchronizing the expansion of a cloud chamber with lightning flashes and comparing the results with random expansions. Some small excess was discovered so that the author called his results ‘not conclusive, but encouraging’ and consistent with the Schonland and Viljoen paper. Clay [8] studied the anomalous barometric effect during thunderstorms at Bandoeng. He found the decrease of ionization in the presence of clouds and (sometimes, but not always) a strong electric field recorded at the same time. Much later, Clay *et al* [11] described an event of increasing cosmic ray intensity during a thunderstorm at Amsterdam. Six independent instruments had detected this increase. An increased ionization was also found during heavy rainfall.

Steinmaurer [9] used in his experiments in the Alps the ionization chamber that was shielded by 10 cm of lead or unshielded. At thunderstorms he found some increase (0.8%) of ionization for the unshielded chamber and a small decrease of ionization for the shielded chamber.

In 1968, Fazzini *et al* [12], using the Bologna scintillation telescope for cosmic ray studies observed transient cosmic ray variations with an amplitude of $\sim$1% and a duration of 10–20 min. In later publications of this group [13, 14] these events (called microvariations) were ascribed to strong temperature variations during passages of cold atmospheric fronts.

Thus, the situation was rather paradoxical at that time: geophysicists tried to find the electrons accelerated during thunderstorms, while cosmic ray physicists who had all possibilities of observing these electrons (and some of them, perhaps, did observe such electrons) obviously preferred to interpret all effects as produced by variations of other meteorological parameters. Chudakov and his collaborators in early 1980s made a decisive step to the electric field interpretation [1]. When first events similar to those observed by the Bologna group were detected at Baksan in 1979, Chudakov recommended to Sborshikov to manufacture an electric field meter and to start regular measurements of correlations with the electric field. The results obtained in these experiments can be summarized as follows.

Table 1. List of experimental searches for energetic electrons, correlations with lightning, and cosmic ray effects during thunderstorm periods.

Experiment and reference	Location	Technique	Electric field measured	Count changes or correlation with lightning
Schonland (1930) [4]	South Africa	Ionization chamber	Yes	−20–30%
Schonland and Viljoen (1933) [5]	South Africa	GM tubes	No	LC
Halliday (1934) [7]	UK	Cloud chamber	No	LC
Steinmaurer (1935) [9]	Alps	Ionization chamber	No	CI for unshielded chamber, CD for shielded
Clay (1933) [8]	Bandoeng	Ionization chamber	Yes	−20%
Clay *et al* (1952) [11]	Amsterdam	Ionization chambers and counters	No	+4–6%
Fazzini *et al* (1968) [12]	Bologna	Scintillators	No	−1%
Alexeenko *et al* (1985) [1, 21]	Baksan	Scintillators	Yes	−1% hard + 2% soft
Aglietta *et al* 1999 [24]	Gran Sasso	Scintillators	No	+5%
Chubenko *et al* (2000) [21]	Tien Shan	GM tubes, scintillators	No	+3.5%
Takami *et al* (2001) [25]	Norikura	Prop. counters, scintillators	No	+1%
Alexeenko *et al* (2001) [27, 28]	Baksan	Scintillators	Yes	Different effects for hard and soft, LC

Note: LC denotes a correlation with lightning, while CI and CD mean the count increase and count decrease, respectively.

Short disturbances of cosmic ray intensity with durations of less than 1 h were shown to be a regular phenomenon taking about 1% of calendar time. It was demonstrated that temperature and pressure effects could not be the main cause of these disturbances. In contrast, the electric field was found to be responsible at least for some of the short disturbances of the counting rate of cosmic ray particles. A very good correlation was obtained for the time intervals when the counting rate and electric field were disturbed (correlation between t_I and t_E). In addition, no microvariations were observed in winter months, when thunderstorms are extremely rare. Thus, it was concluded in [1] that the correlation with the electric field is established without doubt. It should also be emphasized that basic mechanisms of the electric field influence were discussed, and in [23] some results of the calculations for the muon mechanism were published.

This pioneering experiment was important in one more respect. Chudakov and Sborshikov (I offer my apologies to other authors who participated in this work, but these two were really key figures in the experiment) tried to study the effect at two different energy thresholds—a very fruitful idea, as will be seen below. Unfortunately, this experiment was terminated after the untimely death of Sborshikov in 1991, and its results were published only as conference papers. But the problem studied in these papers became popular again in the 1990s when the theory of runaway breakdown was developed. Table 1 presents the data (this list is far from being complete) on basic experiments made both before and after the appearance of this theory.

3. Runaway breakdown theory

The term 'runaway electrons' was coined by A Eddington as early as 1926 following Wilson's hypothesis [2, 3]. And the theory of runaway breakdown developed in early 1990s is neither less nor more than this idea of Wilson formulated as a concrete theoretical model. One can

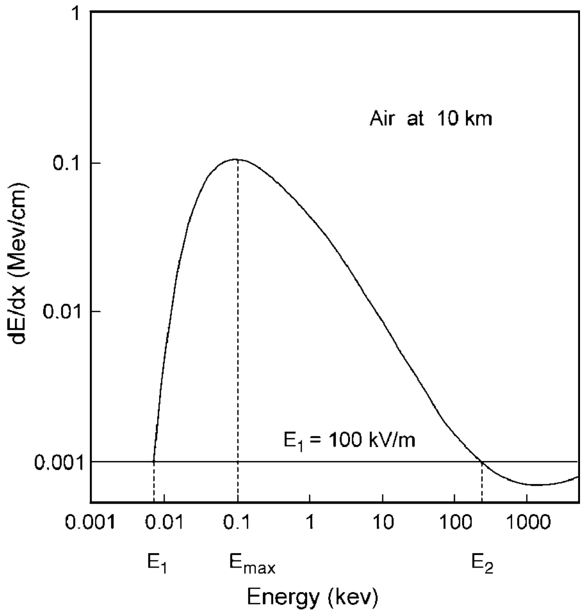

Figure 1. Stopping power of air for electrons at a height of 10 km.

find the main issues of this theory in [15, 16], and [17] presents a nearly exhaustive review of all related problems. Here, only very popular comments about the theory are to the point.

Figure 1 taken from [19] demonstrates the ionization losses for electrons in air at an altitude of 10 km as a function of energy. The horizontal line $E_t = 100\,\text{kV m}^{-1}$ corresponds to the typical electric field of thunderclouds. The continual acceleration of electrons is possible when the following condition

$$qE_t > \mathrm{d}E/\mathrm{d}x$$

is met, where qE_t is the Lorentz force acting upon an electron of charge q. It is obvious from figure 1 that the acceleration process is possible at $E < E_1$ and $E > E_2$. The electrons of ionization in the first region can produce electron avalanches resulting in a usual dielectric breakdown. In the second region, acceleration is also possible if there are particles that can be injected into this region directly. Secondary electrons produced by cosmic rays are ideal seed particles for further acceleration. Delta electrons knocked out by accelerated electrons can appear in the same energy region and be accelerated too. So, a very interesting physical process occurs: a cascade of relativistic electrons whose multiplication continues until the electric field exists. May be precisely this process is the main regulator that limits the electric field in the atmosphere. This model gives an answer to the main problem of lightning physics: why the lightning discharge takes place at voltages about an order of magnitude lower than the usual breakdown voltage? A special term 'breakeven field' (as opposed to breakdown) was even introduced for this field of lightning generation [18]. There are many details of this qualitative picture, which are to be elucidated and verified. But it seems at the moment that some process of this kind should inevitably exist.

One prediction of the theory of runaway breakdown is the generation of a considerable x-ray flux immediately before the lightning. So, some experiments were performed to search for this x-ray emission. Among them, the balloon experiment [19] claimed a positive result, while the ground-based search [20] was unsuccessful. The Tien Shan experiment [21] is

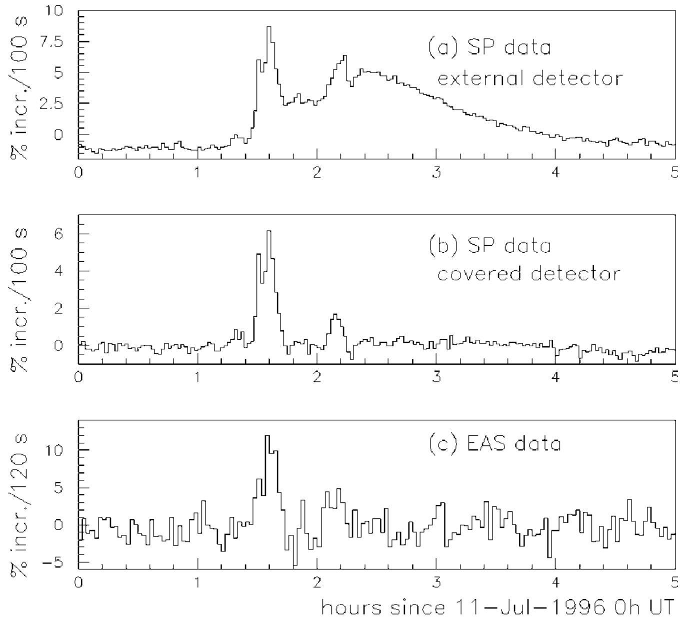

Figure 2. The EAS-TOP data during the 11 July 1996 event. The upper and middle panels present the data for energy thresholds 2.5 and 25 MeV, respectively.

also mainly aimed at searching for x-ray pulses correlated with lightning strokes. It may well be, however, that not only x-rays generated by accelerated electrons, but these electrons themselves can be detected.

4. Recent experiments

It is interesting to see in table 1 that all recent experiments (four bottom lines) are made with the air shower arrays. There are special reasons for this. First, the total area of EAS array detectors is large so that the high statistical accuracy is easily achievable. Secondly, the energy threshold of detection can be sufficiently small to include the MeV region of runaway electrons. Next, EAS arrays operate continuously and are often located at the mountain level. The latter circumstance can be important according to the runaway breakdown theory.

A typical pattern of the thunderstorm effect at the EAS-TOP array is shown in figure 2. This event detected on 11 July 1996 demonstrates perhaps the maximum of what can be observable without electric field measurements. A NaI(Tl) detector was used for low energy measurements in several intervals, the counting rates of array scintillators were recorded at two energy thresholds (2.5 and 25 MeV), and even the counting rate of showers with energies above 100 TeV was analysed. One can see in figure 2 that at low energy threshold $E >$ 2.5 MeV (upper panel) there is a long (2–3 h) enhancement with a maximum of about 5%. Two narrow peaks with duration of about 10 min are superimposed on the background of this broad maximum. At higher energy threshold $E >$ 25 MeV (middle panel) both narrow peaks are still observed, while no broad maximum is present. Therefore, the authors [24] interpreted the broad maximum as produced by the radon washout effect during rainfall, which seems to be a fairly reasonable explanation. The narrow peaks were interpreted as the effect of strong atmospheric electric fields, similar to that of Chudakov and Sborshikov.

It should be noted that the experiment on Mt Norikura [25] also detected similar patterns during thunderstorms: 'long-lived' events with duration of about 2 h and 'short-lived' events about 10 min long. On 8 August 2000, both the types were recorded by proportional counters with low threshold, and only short-lived events were observed for scintillators with the threshold $E > 20$ MeV (see figure 1 in [25]).

Basically the same structures were detected by the Tien Shan group [29]. In this experiment, the air shower array was supplemented by a system of Geiger–Müller counters installed to detect the x-ray emission of lightning predicted by the runaway breakdown theory. The bursts on a time scale of 1 min were simultaneously detected by GM counters at different points of observation and interpreted by the authors [21] as the x-ray bursts they were searching for. These bursts were observed against the background of broad counting rate increases that were also interpreted as the radon washout effect. Since no electric field was recorded, it was impossible to correlate the data with lightning strokes or field irregularities. Currently, the electric field measurements have been started both by the Tien Shan [29] and Norikura [30] groups, so one can expect the new interesting experimental data to appear in the near future.

At the moment, however, only one experimental group succeeded in studying the correlations of cosmic ray counting rate with the electric field strength.

5. Baksan results

This experiment is a continuation of the old Baksan experiment with two considerable improvements: (1) the data on cosmic ray and electric field intensity are sampled every second (the experiment [1, 23] used a 4 min output) and (2) the data on the hard and soft components of cosmic rays are fully separated. The Baksan air shower array (BASA) includes the so-called Carpet of 400 scintillators with a total area of 200 m^2 in the building with a rather thick concrete roof (21 g cm^{-2}) and six huts each containing 9 m^2 of scintillators (54 m^2 in total) with only a very thin covering. For this experiment, the energy threshold of the detectors under the roof was 30 MeV (together with 40 MeV of ionization losses in the roof this gives the effective threshold for charged particles 70 MeV). For uncovered scintillators two integral discriminators with thresholds 10 and 30 MeV allowed the soft component to be isolated within these limits. The counting rates of thus isolated soft and hard components (4000 s^{-1} and 40 000 s^{-1}, respectively) were correlated with the electric field strength during periods of thunderstorm activity. The field meter of the 'electric mill' type was installed in the centre of the array, on the roof of the building where the Carpet is located. The results of observations in the summer season of 2000 are published in [27, 28]. The regression curves for the soft and hard components (pressure-corrected) versus the electric field are shown in figures 3 and 4, respectively.

Now it is clearly seen why it was necessary to separate the components: the effect is essentially different, even opposite, for the soft and hard components. Generally, the net effect of the electric field is the increasing intensity for the soft component and decreasing intensity of the hard component. Moreover, the linear term dominates for the soft component, while for the hard component the quadratic term is dominant. Finally, the quadratic term for the soft component (if any) is of the opposite sign with respect to that for the hard component. Accordingly, two different mechanisms are responsible for the total effect. In [1], these mechanisms were referred to as the e-mechanism and μ-mechanism, though at that time Chudakov and Sborshikov failed to observe them. Now the Baksan group at last succeeded in doing this. It is interesting that in both the cases a fairly regular behaviour of the regression

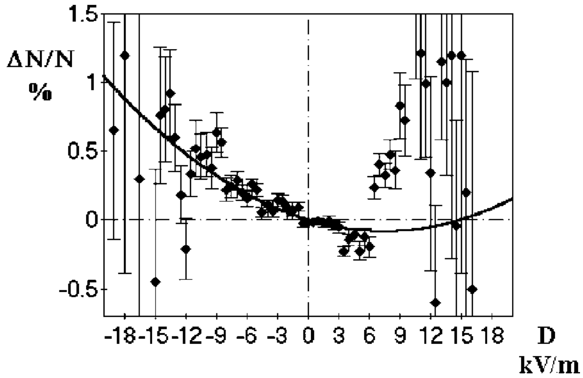

Figure 3. The amplitude of the soft component relative variation versus the electric field strength. Observations were made at Baksan in 2000 and 11 thunderstorms are included in the analysis.

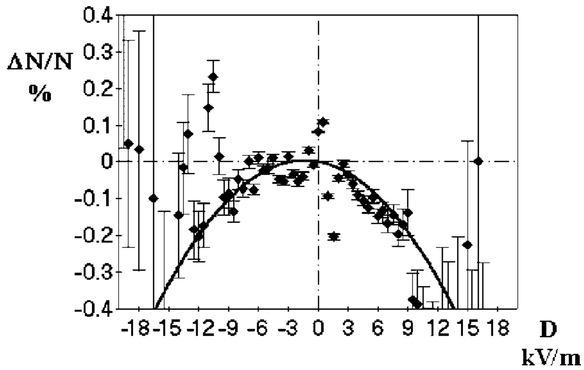

Figure 4. The amplitude of the hard component relative variation versus the electric field strength. Observations were made in 2000 at Baksan and 14 thunderstorm periods are included in the analysis.

curves is limited by relatively moderate fields ($\pm$7–10 kV m^{-1}), while at stronger fields the deviations from regression lines are probably associated with some, as yet unknown, irregular processes. One can see in figure 5 what kind of irregularity is possible to observe, where the most spectacular event recorded on 7 September 2000 is demonstrated. During a very complicated disturbance of the electric field (top panel) one can observe a strong effect in the soft component (second panel from the top) and virtually no effect in the hard component (the third panel). The lower panel presents the measurements of the electric current of rain. The slow trend in the hard component is interpreted as a result of changing temperature in the upper atmosphere. Figure 5 presents the data for a rather long period with averaging over 4 s intervals. The fine structure of this event is shown in figure 6, where individual lightning strokes are clearly seen in both the top and bottom panels, recorded by two independent instruments. It is obvious that the counting rate of the soft component increases just before some of these lightning strokes. The largest increase is equal to 20% of intensity and demonstrates the exponential growth with a subsequent abrupt drop to the mean value. The effect is highly reliable from the viewpoint of statistics: at least 20 points show statistically significant excess, the largest one being as high as 13 standard deviations (σ = 1.5%). This largest increase is

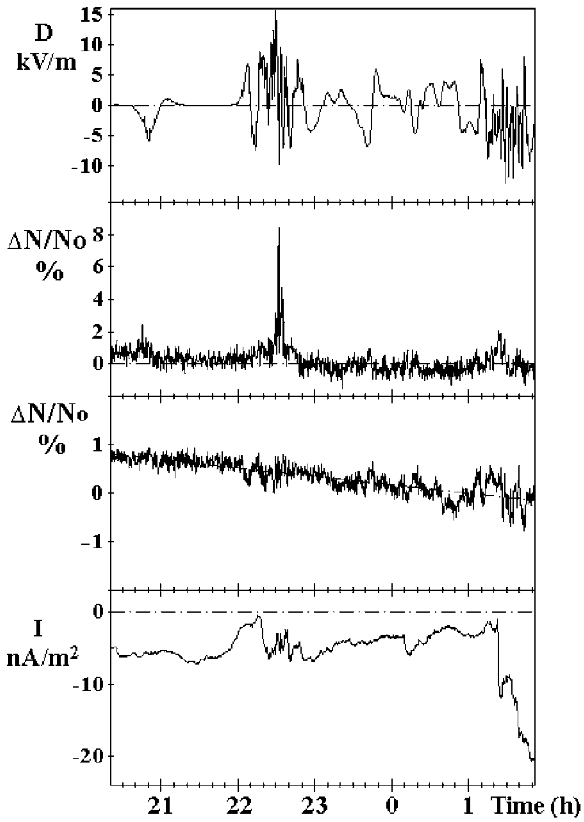

Figure 5. Strong enhancements of the soft component (second panel from the top) during the thunderstorm on 7 September 2000. The interval of averaging is 4 s. No effect is observed for the hard component (the second panel from the bottom) except for a long trend presumably due to temperature variation at high altitudes.

also remarkable by its precise exponential character. When its profile is approximated by the formula

$$\frac{\Delta N}{N_0} = A \exp\left(\frac{t - t_0}{\tau}\right),$$

the e-folding value is $\tau = 11.4 \pm 0.1$ s.

The fine structure with multiple pre-lightning enhancements is a specific feature of this event so that one can doubt about the same nature of this phenomenon with that of EAS-TOP event in figure 2. Another event recorded at Baksan one year later, on 26 September 2001 looks more similar to the EAS-TOP event (see figures 7 and 8). The striking difference with figure 6 is a longer time of the enhancement and the absence of an abrupt drop. Nevertheless, this new event correlates with a lightning stroke too. The point is that now the polarity of lightning is different as compared to figure 6. Another very important distinction of figure 7 is a significant effect in the hard component, although it is naturally less pronounced than in the soft component. This obviously means that the spectrum of accelerated particles in this latter event is harder than the spectrum in the former event of figure 6.

The fact that the pre-lightning enhancement in the case of 26 September 2001 event was observed also below the roof, allowed the absorption coefficient to be determined for the

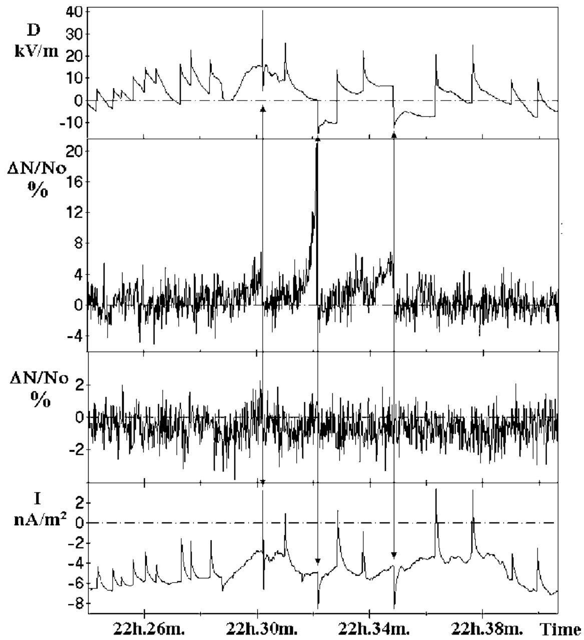

Figure 6. The fine structure of the event of figure 5. The best possible time resolution of 1 s. Correlation of exponential increases with lightning strokes is without doubt.

additional component that produced the enhancement. This was done in [35] using the data without the roof and under it at one and the same energy threshold. The absorption coefficient thus determined turns out to be equal to 31.8 g cm^{-2}, which is more or less consistent with the absorption of the usual soft component. The bottom panel of figure 7 presents the data of the large-area muon detector with an energy threshold of 1 GeV. There is no effect in the flux of muons of these energies.

6. Discussion

Thus, the following experimental facts have been observed during thunderstorms:

(1) large enhancements of low energy particles with a typical time scale of a few hours;
(2) correlations of the soft and hard component intensities with the electric field strength; and
(3) significant pre-lightning enhancements in the soft component (mainly) whose characteristics probably depend on the lightning polarity.

Most people agree that phenomenon (1), observed by several groups (EAS-TOP, Tien Shan and Norikura), is not related to cosmic rays being caused by the precipitation of radon daughter nuclei during the rainfall. So, strictly speaking, only phenomena (2) and (3) are in accordance with the title of this paper. They are observed at the moment by only one group and, certainly, need to be confirmed. Nevertheless, it is important to note that both of them could be expected to exist. This is especially true as far as the electron and muon mechanisms of item (2) are concerned. Both were discussed in [1, 23], and the effect of the muon mechanism was even calculated in [23]. As for item (3), it can appear a matter of the largest interest for future studies of electric phenomena in the atmosphere using cosmic rays.

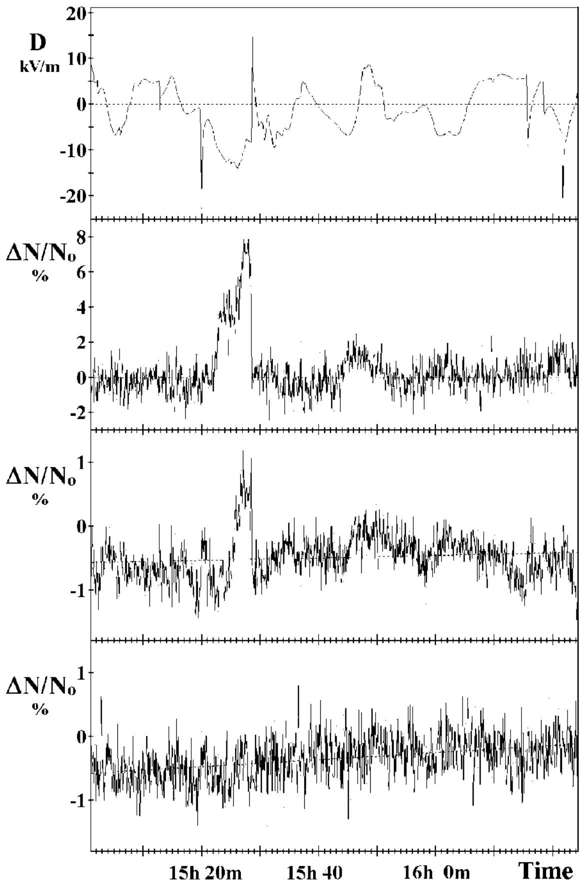

Figure 7. A thunderstorm event observed at Baksan on 26 September 2001. The soft component enhancement (second panel) is similar to the EAS-TOP event of figure 2. Some effect is observed in the hard component too (third panel). The bottom panel presents the counting rate of 1 GeV muons.

Meteorological effects of cosmic rays are being observed for several decades. There is even a special monograph [31] devoted to this issue. However, originally the main aim of research in this field was to exclude these meteorological effects in order to observe the true behaviour of cosmic ray fluxes. The experiments reviewed in this paper have the aim that is almost opposite. It can be formulated as follows: knowing the regular behaviour of cosmic rays, to use them for probing some of the geophysical parameters (electric field of the thunderstorm atmosphere in this particular case). These investigations can be considered as applied from the point of view of cosmic ray physics. However, they can appear to be quite fundamental for geophysics. I believe that we are only at the beginning of a very promising line of research, though even these first experimental results yield very important and partially unexpected data.

One more point should be emphasized in this connection. In recent years, especially after the discovery of surprisingly good correlation [32] between the global low cloud cover measured by satellites and the GCR intensity, cosmic rays have become popular as a candidate for the agent influencing the meteorological phenomena. There are attempts to study the effect of cosmic rays on clouds by imitating the conditions of permanent irradiation with a cloud

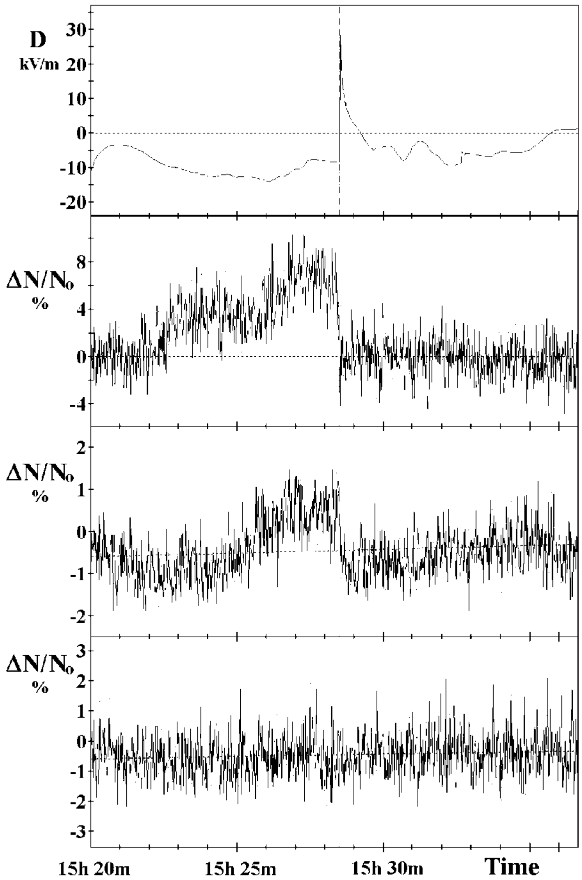

Figure 8. The event of figure 7 on a more detailed scale. The lightning stroke is well seen in the upper panel representing the electric field record. The coincidence of the particle enhancements with this lightning is obvious.

chamber at accelerator (experiment CLOUD at CERN [33]). So, cosmic rays probably play a very important role in atmospheric processes on a global scale (see the paper by Yu I Stozhkov in this issue). The subject matter of this paper is perhaps indicative of equally important role played by cosmic rays in fundamental atmospheric processes on very limited scales (both in space and time).

7. Conclusion

Thus, in almost 80 years Wilson's original idea is popular again and is being extensively developed by both theorists and experimentalists. It opens up a new field of research for cosmic ray physics. Though Wilson himself did not have cosmic rays whatsoever in mind, now it seems that their role can appear unexpectedly important in all atmospheric processes, including electric ones.

So far, the experimental results on cosmic rays during thunderstorms have been obtained as a by-product in the large-scale experiments with extensive air shower arrays. One should expect, however, that specific experiments will be planned soon to study the interrelations of the electric field and cosmic ray intensities.

Not only lightning processes can be interrelated with cosmic ray phenomena. The runaway electrons are invoked for the explanation of red sprites too (see, for example, [34]). The electric discharges of new types discovered in recent years (sprites, elves and jets) may be more or less subject to cosmic ray influence. To find the details of the mechanisms of this influence is a challenge for cosmic ray physics.

Acknowledgment

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